LANDFORM GRADING AND SLOPE EVOLUTION

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ABSTRACT: Transportation corridors and residential developments in steep terrain both require that some grading be carried out to accommodate roadways and building sites. The manner in which this grading is planned and executed and the nature of the resulting topography or landforms that are created affect not only the visual or aesthetic impact of the development but also the long-term stability of the slopes and effectiveness of landscaping and revegetation efforts. Conventionally graded slopes can be characterized by essentially planar slope surfaces with constant gradients. Most slopes in nature, however, consist of complex landforms covered by vegetation that grows in patterns that are adjusted to hillside hydrogeology. Analysis of slope-evolution models reveals that a planar slope in many cases is not an equilibrium configuration. Landform-graded slopes on the other hand mimic stable natural slopes and are characterized by a variety of shapes, including convex and concave forms. Downslope drains either follow natural drop lines in the slope or are hidden from view in swale-and-berm combinations. Landscaping plants are placed in patterns that occur in nature as opposed to random or artificial configurations. The relatively small increase in the costs of engineering and design for landform grading are more than offset by improved visual and aesthetic impact, quicker regulatory approval, decreased hillside maintenance and sediment removal costs, and increased marketability and public acceptance.

INTRODUCTION

All slopes are subject to erosion and mass wasting. Various measures can be invoked to slow, if not completely prevent, this degradation. Biotechnical slope-protection methods, for example, have attracted increasing attention as a cost-effective and visually attractive means of stabilizing slopes. This approach has been used to stabilize and revegetate cut-and-fill slopes along highways as well as slopes in residential hillside developments. Kropp (1989) described the use of contour wattling in combination with subdrains to repair and stabilize a debris flow above a housing development in Pacifica, California. Gray and Sotir (1992) described the use of brush layering to stabilize a high, unstable cut slope along a highway in northern Massachusetts. Brush layering and other soil bioengineering measures have likewise been employed (Sotir and Gray 1989) to repair a failing fill embankment along a highway in North Carolina.

Transportation corridors and residential developments in steep terrain both require that some excavation and regrading be carried out to accommodate roadways and building sites. The manner in which this grading is planned and executed and the nature of the resulting topography or landforms that are created affect not only the visual or aesthetic impact of the development but also the stability of the slopes and effectiveness of landscaping and revegetation efforts.

Succinct descriptions and comparative definitions of grading designs are as follows.

Conventional Grading

Conventionally graded slopes are characterized by essentially linear (in plan), planar slope surfaces with unvarying gradients and angular slope intersections. Resultant pad configurations are rectangular.

Slope drainage devices are usually constructed in a rectilinear configuration in exposed positions.

Landscaping is applied in random or geometric patterns to produce "uniform coverage."

Contour Grading

Contour-graded slopes are basically similar to conventionally graded slopes except that the slopes are curvilinear (in plan) rather than linear, the gradients are unvarying, and profiles are planar. Transition zones and slope intersections generally have some rounding applied. Resultant pad configurations are mildly curvilinear.

Slope drainage devices are usually constructed in a geometric configuration and in an exposed position on the slope face.

Landscaping is applied in random or geometric patterns to produce "uniform coverage."

Landform Grading

Landform grading replicates irregular shapes of natural, stable slopes. Landform-graded slopes are characterized by a continuous series of concave and convex forms interspersed with swales and berms that blend into the profiles, nonlinearity in plan view, varying slope gradients, and significant transition zones between man-made and natural slopes. Resultant pad configurations are irregular.

Slope drainage devices either follow "natural" slope drop lines or are tucked away in special swale-and-berm combinations to conceal the drains from view. Exposed segments in high visibility areas are treated with natural rock.

Landscaping becomes a "revegetation" process and is applied in patterns that occur in nature: trees and shrubs are concentrated largely in concave areas, whereas drier convex portions are planted mainly with ground covers.

GRADING APPROACHES

Conventional

Conventional grading practice often results in drastically altered slopes and the replacement of natural hillside forms with artificial, sterile, and uniform shapes and patterns. Conventionally graded slopes can be characterized by essentially planar slope surfaces with constant gradients and angular intersections as shown in Fig. 1. Slope-drainage devices are usually constructed in a rectilinear and exposed fashion.

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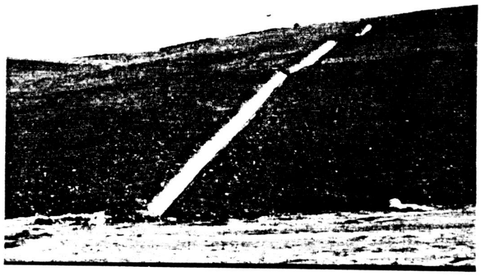

FIG. 1. Conventional Grading with Planar Slopes and Rectilinear Drainage Ditch in Highly Visible and Exposed Location

FIG. 2. Conventionally Graded Hill Slope with Planar Face, Rectilinear Drainage Ditch, and uniformly Spaced Plantings

Grading specifications in southern California, for example, typically call for flat, planar 2:1 ($H:V$) slopes with a midslope bench and a drainage ditch, commonly placed straight down the slope, that collects and conveys water from brow and midslope bench or terrace drains, respectively. Landscaping and plants are applied in random or geometric patterns as shown in Fig. 2.

Contour Grading

Contour grading offers a slight improvement over the sterile and simple geometry achieved by conventional grading. Some scalloping or curvilinear appearance is introduced onto the slope when seen in plan view; however, the slope gradients or profiles remain planar and unvarying. Transition zones at the bottom and top of slopes may also have some rounding applied. Slope drainage devices are still constructed in the same geometric configuration and exposed position on the slope face as in conventional grading. Landscaping and plants are also applied in random or geometric patterns.

Landform Grading

"Landform grading" essentially attempts to mimic nature's hills. This approach has been largely developed and pioneered by Schor (1980, 1992, 1993), who has successfully applied landform grading to several large hillside developments and planned communities in southern California. It is important to note that very few hillsides are found in nature with linear, planar faces. Instead, natural slopes consist of complex landforms covered by vegetation that grows in patterns that are adjusted to hillside hydrogeology, as shown in Figs. 3 and 4. Accordingly, landform-graded slopes are characterized by a variety of shapes including convex and concave forms interspersed with ridges and elbows in the slope.

Downslope drain devices either follow natural drop lines in the slope or are tucked away and hidden from view in special concave swale and convex berm combinations as shown in Fig. 5. Landscaping plants are not placed in random or artificial patterns. Instead they are applied in patterns that

FIG. 3. Natural Hill Slopes with Multiple and Complex Shapes and Profiles

FIG. 4. Natural Hill Slopes Showing Vegetation Patterns

FIG. 5. Example of Landform Grading with Drainageway that is Placed in Special Swale-and-Berm Combination to Conceal it from View

occur in nature (see Fig. 6). Trees and shrubs are concentrated primarily in concave areas, where drainage tends to concentrate, while drier convex portions are planted primarily with herbaceous ground covers. A schematic depiction of conventional site planning versus landform site planning is shown in Fig. 7.

SLOPE-EVOLUTION CONSIDERATIONS

Landform-graded slopes present more than a varied and pleasing visual appearance. They also tend to be intrinsically more stable. The general lack of straight, planar slopes in nature says something. Slopes wear away or degrade over time by gravity-driven forces of erosion and mass wasting. The slopes proceed toward an equilibrium profile, which evidently does not include a linear and unvarying gradient.

Geomorphologists have been interested for some time in various slope-evolution models. The spatial and temporal variation of any point in a slope can be expressed by a number of two-dimensional mathematical models. These models predict the rate of change of elevation (dY/dT) of any point on a slope with elapsed time (T) and coordinate location (X, Y). Examples of these mathematical models are the following:

$$\text{Model \#1 } dY/dT = -A \tag{1}$$

$$\text{Model \#2 } dY/dT = -B\,(dY/dX) \tag{2}$$

$$\text{Model \#3 } dY/dT = -C\,(\text{height above base}) \tag{3}$$

$$\text{Model \#4 } dY/dT = -D\,(\text{distance from crest})^{0.6} \tag{4}$$

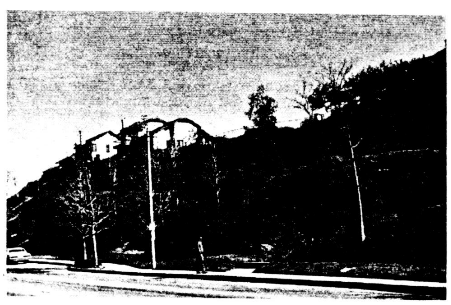

FIG. 6. Example of Landform Grading and Revegetation with Concave and Convex Slope Forms and Nonlinear, Varying Slope Gradients

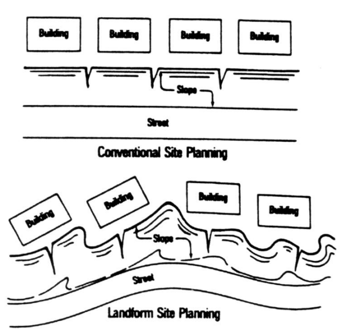

FIG. 7. Plan View of Conventional versus Landform Site Planning

$$\text{Model \#5 } dY/dT = -E\,(d^2Y/d^2X) \tag{5}$$

Graphical illustrations or simulations of these models are shown in Figs. 8–12. Each of these mathematical models has some physical basis. Model #2, for example, describes the "parallel retreat of slope" concept, which postulates that upon reaching its limiting slope angle (angle of repose) a slope retreats back at a constant inclination. A purely frictional, sandy slope whose stability is independent of slope height could conceivably fit this model. Model #4 fits observations from the Universal Soil Loss equation, which indicates that rainfall erosion losses from a slope (all other factors equal) are a function of the slope length. Model #5 is the so-called diffusion model, which postulates that in a transport-limited slope the passage of material down the slope from a point above is limited by the transfer rate at a point below. The slope profile adjusts itself over time to optimize this stepwise or sequential transfer of material downslope by various erosion or mass-wasting processes. Note that in the diffusion model, an initially planar slope evolves over time into a concave-convex slope as shown in Fig. 12.

The diffusion model (#5) was tested as part of a doctoral dissertation on slope evolution models at the University of

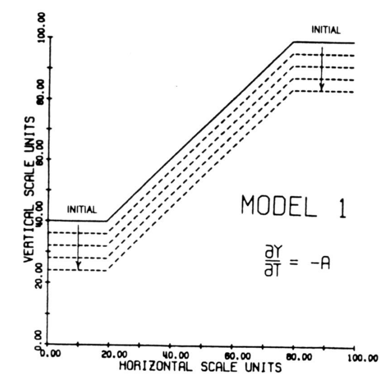

FIG. 8. Evolution of Hillside Slope when Rate of Lowering is Uniform over Entire Slope Profile (Model 1) [from Nash (1977)]

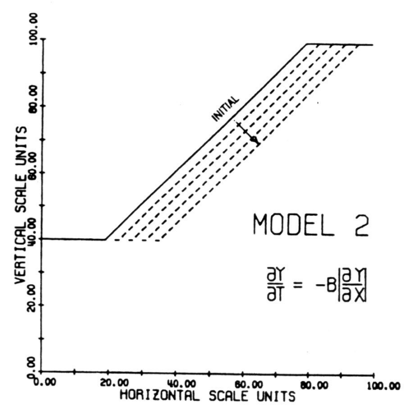

FIG. 9. Evolution of Hill Slope when Rate of Lowering at Point on Slope is Proportional to Profile Gradient at Point (Model 2) [from Nash (1977)]

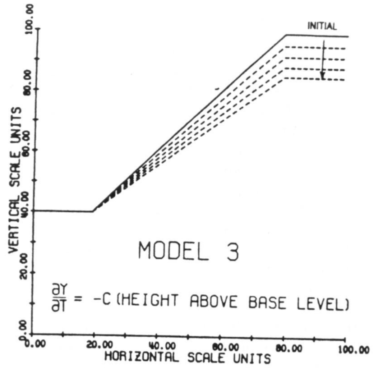

FIG. 10. Evolution of Hillside Slope when Rate of Lowering of a Point on Slope is Proportional to Elevation of Point (Model 3) [from Nash (1977)]

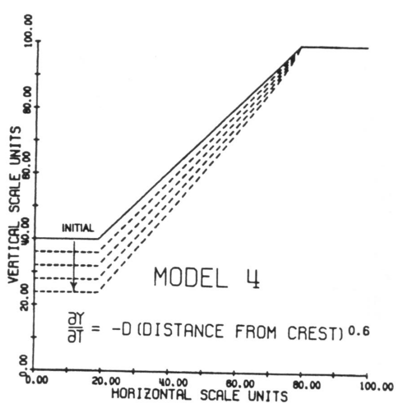

FIG. 11. Evolution of Hill Slope when Rate of Lowering at Point on Slope Profile is Proportional to Distance that Point Lies from Crest or Divide (Model 4) [from Nash (1977)]

Michigan (Nash 1977). The slope profiles of present-day, modern wave-cut bluffs along Lake Michigan and those of ancient, abandoned bluffs marking former glacial lake margins were used for this purpose. The study assumed that slope processes at work on the bluffs have remained relatively constant over geologic time. The ancient bluffs and their ages respectively, are the Nipissing bluffs (4,000 yr) and Algonquin bluffs (10,500 yr). Actual slope profiles for these three bluffs superposed at their midpoint are shown in Fig. 13. The correspondence or fit between the profiles predicted by the diffusion model and the actual profiles was examined for various diffusion constants. The configurations predicted by the diffusion model for an abandoned bluff after 4,000 years and 10,500 years using a diffusion coefficient of 0.012 m^2/yr and an initial, planar profile similar to the profile of the modern bluff are shown in Fig. 14. According to the diffusion model, the slope profiles gradually change over time from a linear to a concave-convex configuration, as illustrated in Fig. 14.

The fit or correspondence between actual and predicted profiles is quite good as can be seen by comparing slope profiles in Figs. 13 and 14. More importantly, this modeling work indicates that in transport-limited slopes, at least, a planar slope with constant inclination, typical of conventional grading practice, is not a stable, long-term equilibrium slope.

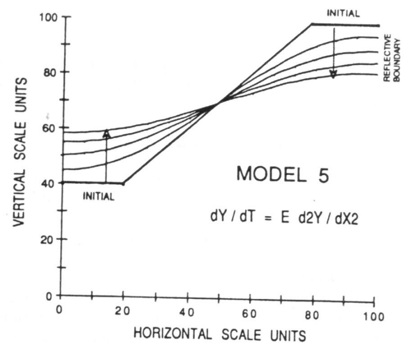

FIG. 12. Evolution of Hillside Slopes when Rate of Lowering of Point on Slope Profile is Proportional to Profile Curvature at that Point, Assuming Reflective Left and Right Boundaries (Model 5) [from Nash (1977)]

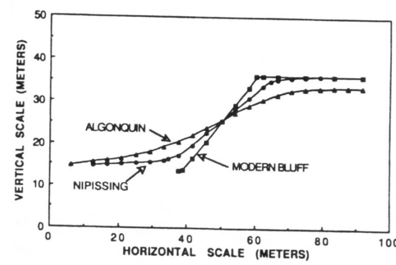

FIG. 13. Modern Bluff Profile, Nipissing Bluff Profile (4,000 yr), and Algonquin Bluff Profile (10,500 yr) Superposed at their Midpoint [from Nash (1977)]

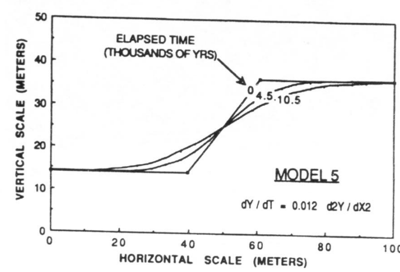

FIG. 14. Slope Profiles Predicted by Model 5 for Initial Planar Slope after 4,000 and 10,500 Years of Elapsed Time Using Diffusion Coefficient of 0.012 m^2/yr and Initial Inclination Similar to Present Wave Cut Bluff [from Nash (1977)]

REVEGETATION AND LANDSCAPING

If monotony and uniformity in grading are combined with a uniform or artificial pattern of revegetation, the overall effect is not only sterile and ugly but also ineffective. Successful and attractive revegetation must invoke the same concepts and approaches as landform grading. Vegetation patterns that are found in nature should also be mimicked. Shrubs and other woody vegetation growing on natural slopes tend to cluster in valleys and swales where moisture is more abundant. Random patterns or uniform coverage should be avoided. Instead, the vegetation is placed where it makes sense, i.e., where it has a better chance of surviving and does a better job of holding soil. Trees and shrubs require more moisture, and they also do a better job of stabilizing a soil mantle against shallow mass wasting. Accordingly, it makes sense to cluster them in swales and valleys in a slope (see Fig. 15), where runoff tends to concentrate and evaporation is minimized. Shrubs should also be heavily concentrated along the drainage flow of each swale.

By purposely controlling the drainage patterns on a slope, runoff can be concentrated in concave areas where it is needed or where it can best be handled by woody slope vegetation (see Fig. 16). Conversely, runoff and seepage will be diverted away from convex areas. These areas should be planted with grasses or more drought-tolerance herbaceous vegetation. Irrigation needs are thus reduced by careful control of drainage pattern on a slope and selection of appropriate plantings for different areas.

IMPACT ON DEVELOPMENT COSTS

Design Engineering and Surveying Costs

Design and surveying can be measurably higher if it is initially performed by a team only experienced in conventional methods. Design engineering and construction staking

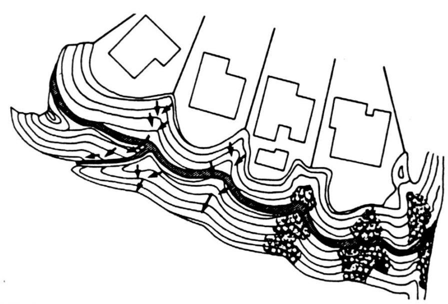

FIG. 15. Topographic Representation of Landform Configuration Showing Radial Flow of Water, Foliage Placement in Swales, and Lots that Conform with Landform Grading Configuration [after Schor (1992)]

FIG. 16. Landform-Graded Slope with Convex and Concave Slope Shapes, Varying Gradient, Curvilinear Drainage Ditch Concealed in Berm and Swale Configuration, and Clustered Plantings

and surveying costs are directly related to the experience, talent, and versatility of the design engineer and his full understanding of the concept. When first implemented with a totally inexperienced staff during pioneering stages, design cost was 15% higher and field cost 10% higher than conventionally designed and surveyed slopes. From that initial experience, design costs quickly decreased to a factor of 1–3%, and surveying to 1–5% over conventional methods and approaches.

A willingness and an open mind to depart from old concepts are essential elements for realizing the benefits of landform grading. In-depth training of the designer, draftsman, and project manager are indispensable, as well, before attempting the landform-grading method. Approving agencies must also be brought into the information dissemination process so that plan check, permitting and, later, inspection can proceed smoothly.

Construction/Grading Costs

Construction/grading costs are most directly related to the size and volume of earth movement than any other factor. In addition, there is a direct relationship to the competitive marketplace situation at a given time. Competition for larger projects, such as those for 1,000,000 cu yd or more, tends to eliminate adherence to landform-grading standards as a significant factor.

Grading costs in hillsides of largely sedimentary materials and not requiring blasting or extremely heavy ripping range from $0.75 to $1.25 per cubic yard with an average of $1.00 per cubic yard. Variables affecting the unit cost include the quantity of material, the nature of the operating area, i.e., open or confined, the length and steepness of the haul from the cut areas to the fill areas, and the rippability by conventional dozer/scraper equipment.

At first glance it appears that landform-graded projects would be significantly more expensive to construct than conventional ones because of the more intricate details and natural shapes required. However, experience has shown that the differential is minor when compared to the total project cost. This is true because the largest percentage (on average 90%) of the earth volume moved, the mass "X" shown in Fig. 17, can be moved, placed, and compacted in a totally conventional manner. Only the outer slope layers, 20–50 ft thick (or approximately 10% of volume), require specialized shaping. Moreover, even this outer layer can still be placed and compacted with conventional equipment and methods. This outer component needs an additional grade checker for control and a dozer with an experienced operator for final shaping. Accordingly, when costs are reckoned on the basis of the actual additional operations involved they are a minor component, typically on the order of 1% of the total cost.

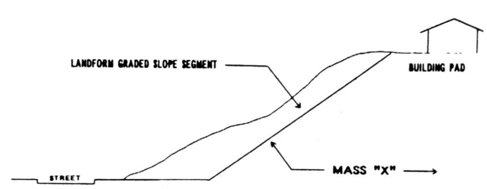

FIG. 17. Relative Amounts and Location of Earth Movement by Conventional as Opposed to Landform Grading

COST-IMPACT COMPARISONS ON VARIOUS SIZE PROJECTS

Large-Scale Projects

On a recently completed hillside project involving 20,000,000 cu yd of earth movement at a cost of some $24,000,000, the total additional cost incurred including design, surveying, construction staking, and grading, was $250,000, or about 1% of the total cost of the grading.

No loss of residential density was encountered, because land planning was done concurrently with the engineering. There was a loss of approximately 1% of commercial pad area due to concave valleys projecting into them. This was offset, however, by the credit given by the governing agency for these indentations toward landscape requirements and coverage calculations for the building pad areas. Furthermore, entitlement approvals were advanced by at least 1 year by being able to mitigate the previous strong community opposition to conventional hillside design and construction methods.

Small-Scale Projects

A 10-acre, 24 custom-lot subdivision requiring 300,000 cu yd of earth movement, initially designed by conventional methods, with little hope for approval, was reconfigured to landform-grading standards. The project applicants had previously proposed conventional grading and had for 2 1/2 years tried to secure permitting agency approvals in a community where grading practices had become a major and highly controversial issue. The governing agency insisted that the applicant apply landform-grading concepts before any further resubmittals. The project was redesigned by adhering to these concepts, and the new layout resulted in 21 lots, a loss of three lots. Design and staking costs also increased by approximately $10,000. However, this revision reduced construction costs by reducing the amount of grading required by 20%. The loss of the lots and additional design costs were further offset by reduced street and storm-drain improvements, tree-removal costs, and an enhanced and aesthetically pleasing project with larger open spaces for each of the lots. This in turn, increased the marketability of the projects. In addition to these benefits, the project received unanimous community approval within 3 months.

APPLICABILITY OF LANDFORM GRADING TO OTHER PROJECTS

In addition to residential and commercial developments the landform-grading concept should lend itself readily to highway slopes. Public objections are often voiced against these highly visible and stark slopes. In addition they are sometimes prone to erosion problems and generation of excess runoff. These problems and objections could be greatly mitigated by the application of this concept, thereby improving public acceptance. This benefit would likely offset any associated additional right-of-way acquisition costs.

Other large earthmoving and shaping projects that result in man-made landforms could also benefit from landform grading. Such projects include sanitary landfills, tailings embankments and mining waste stockpiles, and downstream faces of earthfill dams.

CONCLUSIONS

Grading considerations are very important to the successful stabilization and revegetation of slopes. Conventionally graded slopes can be characterized by essentially planar slope surfaces with constant gradients. Most slopes in nature, however, consist of complex landforms covered by vegetation that grows in patterns that are adjusted to hillside hydrogeology. Analysis of slope evolution models reveals that a planar slope often is not an equilibrium configuration.

Landform-graded slopes, on the other hand, are characterized by a variety of shapes including convex and concave forms that mimic stable natural slopes. Downslope drain devices either follow natural drop lines in the slope or are tucked away and hidden from view in special concave swale and convex berm combinations. Similarly landscaping plants are not placed in random or artificial patterns, but rather in patterns that occur in nature. Trees and shrubs are clustered primarily in concave areas, where drainage tends to concentrate, while drier convex portions are planted primarily with herbaceous ground covers.

Design and engineering costs for landform grading increase approximately 1–3%, and surveying 1–5% over conventional methods. Construction and grading costs are most strongly affected by the volume of earth movement and the competitive market. Accordingly, a landform-grading specification on a large project is not a significant factor. The relatively small increase in the costs of engineering and design are more than offset by improved visual and aesthetic impact, quicker regulatory approval, decreased hillside-maintenance and sediment-removal costs, and increased marketability and public acceptance.

APPENDIX. REFERENCES

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